Failure Conditions of Flexible Culverts Embedded in Soil

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Rule-of-thumb design methods define failure of flexible pipe culvert as 20 percent decrease in the vertical diameter, with 5 percent decrease being considered the maximum allowable deflection for design purposes. Experience has shown, however, that the pipe wall may buckle before 5 percent deflection has been developed. Of course, buckling of the pipe wall in most culvert installations would be considered failure. This research project has established that the type of soil and the degree of compaction are the basic factors which determine whether or not a culvert will fail by buckling before it deflects 5 percent. An approximate range of soil types and the approximate degree of compaction required for buckling failure have been evaluated by model studies. From this information it may be concluded that culvert design becomes one or the other of two distinct problems based on the assumptions of failure by (a) deformation and (b) buckling of the wall. Methods of design in each case are reviewed and discussed.

• FAILURE of a structure is its inability to perform the function for which it is designed. In the case of a flexible pipe conduit embedded in soil, failure might include one or more of the following conditions:

1. Deformation of the conduit to the point where the designed conveyance capacity is impaired. Such deformation may be the results of any of the following:

(a) Ring deformation (deformation of the circular cross-section). This deformation usually results in a decrease in vertical diameter and an increase in horizontal diameter with an approximate elliptical configuration (Fig. 1). In its worst condition the ellipse is distorted to a point where a reversal of curvature occurs on the top or bottom and failure by collapse is imminent (Fig. 2).

(b) Failure of the rivets or bolts in the seam or buckling of the conduit wall, thus decreasing the total effective cross-sectional area (Fig. 2).

(c) Longitudinal or beam deflection of the conduit (Fig. 3).

2. Relative movement of the soil around the conduit such that the soil fill

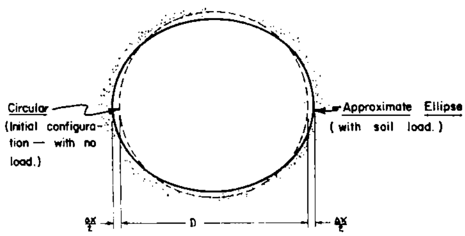

Figure 1. Typical ring deformation under soil fill (approximately elliptical).

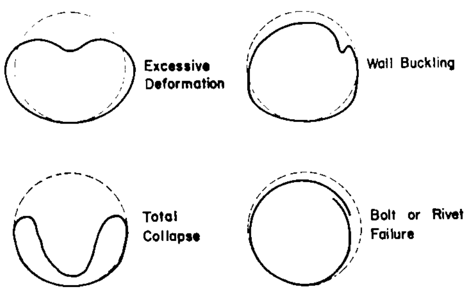

Figure 2. Modes of failure in the ring.

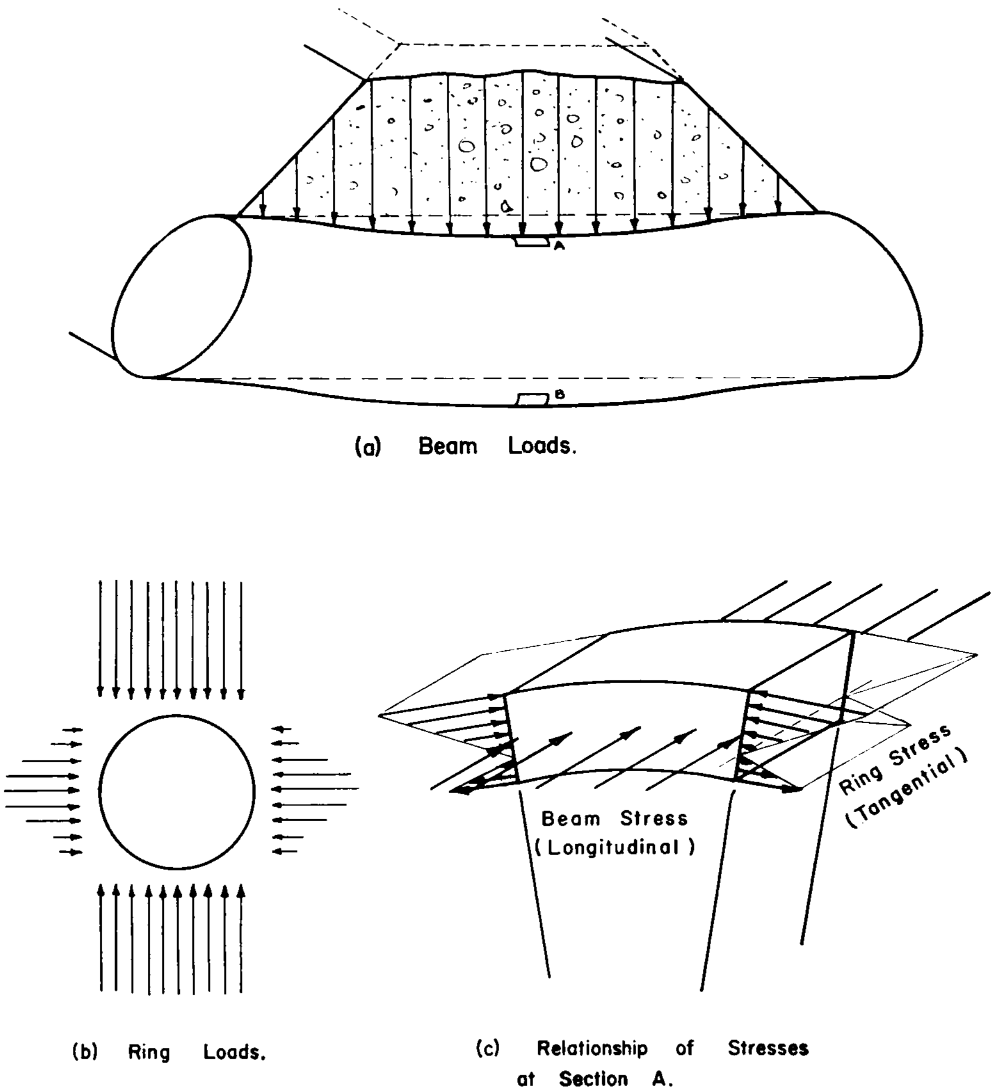

Figure 3. Failure conditions in the beam.

cannot perform the function for which it was designed. For example, if a flexible conduit under the runway of an airfield were to deform so much that a dip developed in the runway surface it must be concluded that a failure has occurred in the soil-conduit system. On the other hand a rise or bump may develop in the runway above that conduit which does not deform as much as the adjacent soil. This condition, too, might be considered as failure of the system.

3. The conduit would surely be classed as a failure if it corroded to the point where soil particles could fall through into the passageway and impair flow, or if leakage were more or less than that permitted in the design. (Some conduits are designed to "leak" where soil is to be drained.)

Proper design of a flexible conduit must take into account all of these possible failure conditions. They are classified according to a logical order of consideration for design as follows:

1. Ring deformation (deformation of circular cross-section).
2. Ring buckling (buckling of the wall cross-section).
3. Longitudinal beam failure.
4. Bolt or rivet failure.
5. Corrosion, leakage, etc.

Unfortunately, in a soil-conduit system it is impossible to anticipate any particular failure condition by considering the properties of the conduit alone or by considering the properties of the soil alone. In every case design must be based on the soil-conduit system. The problem is further complicated by the interrelationship of the various conditions of failure. For example, the amount of ring deformation influences the buckling failure conditions. This follows from the fact that the greater the radius of curvature of the conduit wall, the lower will be the tangential stress at buckling. Shearing of the bolts influences longitudinal beam strength; longitudinal beam loading influences ring buckling; corrosion influences all failure conditions; etc. If all possible failure conditions are considered in terms of all possible soil conditions, design of the soil-conduit system is virtually impossible. Fortunately, approximate results can be obtained by considering each failure condition separately and by designing for each independently. The first problem, then, becomes one of separating and ordering the failure conditions. The second problem is the actual design of the conduit on the basis of each separate failure condition.

As far as order of investigation is concerned it is always wise to design for the most critical conditions first. The problem of separating these considerations so that an independent analysis can be carried out on each is not such a simple matter.

In order to treat corrosion as a separate problem it is usually necessary to prevent corrosion altogether. Either the conduit will corrode and weaken the structure enough to permit failure or it will resist corrosion for the required life of the structure. However, this does not imply that a little corrosion will necessarily cause failure of the conduit. Various degrees of corrosion in the serviceable corrugated metal culverts in California have been observed and measured by the California State Highway Commission (*1*). But until more data are available on corrosion the best that can be done toward permitting corrosion is to arrive at some experience factors for serviceable life of the conduit. In the future, methods may be devised to stabilize the soil around the conduit so that corrosion may be tolerated. If this happens, the rigid requirements for corrosion resistance may be eased and more attention will be devoted to the influence of corrosion on the failure conditions.

The problem of leakage also may be treated as a separate problem. Perforations in drainage pipe should be staggered in such a way that a line of weakness is avoided; otherwise the conduit may buckle. Assuming that corrosion may not be permitted, corrosion and leakage should be considered last in the design of conduits.

Bolt and rivet failure is generally of secondary consideration also. Some culverts have failed by shearing or bearing failure of the bolts or rivets, but recent efforts of the culvert manufacturers include special attention to the seam. In general a conduit will buckle before the bolts or rivets fail. It is true that the seam may increase the stiffness of the wall at that one section, thus altering ring deformation, or it may create a line of weakness where buckling can occur; but in general these effects are small enough to be neglected in the ultimate design of the conduit.

The longitudinal beam action is more difficult to separate from the other conditions which lead to failure; particularly in the case of conduits with cylindrical walls in contradistinction to corrugated walls. In discussing the case of cylindrical walls, maximum direct stresses caused by beam action are at right angles to the direct stresses caused by the ring action

(Fig. 3). The resultant ring load is compression, even though the ring stress may vary from compression at the outside to tension on the inside as the cross-section becomes elliptical. When biaxial stresses in steel act at right angles to each other and are of the same sign the yield point stress is equal to the uniaxial yield point stress. If, however, the biaxial stresses are equal but of opposite sign, the yield point stress is about one-half as much as the uniaxial yield point stress (*2*). But even if the yield point stress in steel were decreased to one-half it would still be in the order of magnitude of 25,000 psi. On the other hand, if a uniform pressure is assumed around the outside of the conduit and if the ratio of diameter to wall thickness is 100, the external pressure required for buckling is about 66 psi (*2*) and the compressive ring stress in the wall is only about 3,300 psi. This is such a small part of the yield stress (even for biaxial stresses with opposite signs) that the biaxial stress effect is negligible. For practical design work it may be concluded that beam stresses and ring stresses may be analyzed separately.

It is highly possible that beam loads may cause failure. To solve such a problem it would be necessary to know something about the settlement of the soil beneath the conduit and the soil load on the top of the conduit. The soil settlement can be predicted approximately by methods of soil mechanics (*4*). The load on the top of the conduit may be more difficult to determine. The Marston theory (*5*) would give only approximate results inasmuch as it was derived without consideration for the longitudinal dimensions.

The beam effect becomes much less significant when the conduit is constructed from corrugated steel, which is used almost exclusively for flexible culverts under highways, airports, etc. In this case the beam stresses are perpendicular to the corrugations and the effect is something like an accordian with considerable beam flexibility. The high beam stresses are reduced materially and the conduit conforms more readily to the settlement of the soil. It is sufficient here to conclude that the beam effect can be considered separately from the other conditions of failure.

Buckling of the ring is a critical consideration in the design of flexible conduits. Approximate solutions for critical buckling pressures can be found in most standard texts on advanced strength of materials (*2*, p. 288). These buckling formulas are based on uniform fluid pressure around the outside of the conduit. In the case of a soil-conduit system the pressures around the outside will tend to equalize and the assumption of uniform pressure may not be in serious error. More work is needed to check this, however. A more difficult decision is whether or not the conduit will fail by buckling or by deformation.

Ring deformation of the conduit is the most widely recognized basis for design. A rational method for predicting the deformation of a conduit has been proposed by Spangler (*6*). Assuming that the conduit cross-section remains elliptical, his formula predicts the increase in horizontal diameter as a function of height of fill and the modulus of soil reaction. This formula is rewritten as

$$\Delta x = \frac{K W_c r^3}{EI - 0.061\ (E')r^3} \tag{1}$$

in which

- Δx = increase in horizontal diameter of the conduit, in in.;
- K = a parameter which is a function of the bedding angle (K = 0.083 for a bedding angle of 180 deg);
- W_c = vertical load per unit length of the conduit at the level of the top, in lb per in.;
- r = mean radius of the conduit, in in.;
- E = modulus of elasticity of the material from which the conduit is constructed, in psi;
- I = moment of inertia of the cross-section of the conduit wall per unit length, in in.^{4} per in.; and
- E' = modulus of soil reaction, a property of the soil.

The modulus of soil reaction is analogous to the modulus of elasticity and may be evaluated for various soil types. Studies have demonstrated that the modulus is related to the basic soil properties, particularly compressibility and degree of compaction (*8*). Moisture content has not yet been completely investigated.

While performing tests on model soil-conduit systems to evaluate E', it was observed that under certain conditions of the soil and under certain values of conduit wall stiffness the conduit failed by ring deformation, but under other conditions it failed by ring buckling of the wall. In the case of ring deformation the increase in horizontal diameter reached a maximum of about 20 percent, after which with increased load the top or bottom of the wall reversed curvature and the conduit collapsed. Typical failure sections are shown in Figure 2. On the other hand, some sections failed by wall buckling before the ring had increased in diameter by as much as 1 percent.

A study was conducted to find out what determines whether a flexible conduit fails by buckling or by deformation and to arrive at the limiting conditions between the two. This is important because the Spangler deflection theory applies only within the range of elastic deformation and cannot describe pipe performance after buckling begins.

A collapsible loading cell (Fig. 4) was constructed. This cell permits application of an axial load on the confined soil with little frictional resistance between the soil and the cell wall. With a model section of conduit in place it is possible to load the pipe to failure. The following procedure was generally followed in the tests conducted on this equipment. The test cell was blocked so that it retained its full height. A mandrel with the model section of the conduit on it was installed horizontally across the center of the cell. Soil was poured into the cell and any excess was screeded off the top. The top plate was then positioned and a pre-compression load was applied to the top cover plate. This pre-compression load made it possible to develop the initial density of the soil surrounding the model conduit section. Following pre-compression, the load was removed and the mandrel was withdrawn from inside the conduit. A load-deformation diagram was then plotted by applying increments of load and measuring the change in the horizontal diameter of the model conduit by means of an inside caliper or transducer.

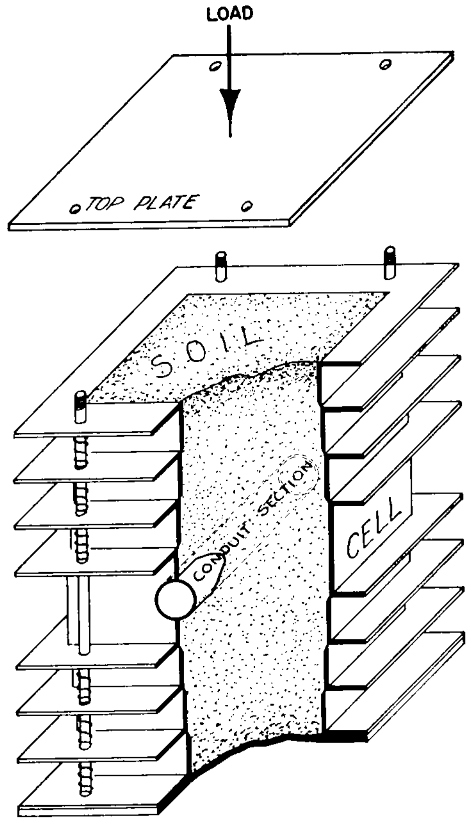

Figure 4. Test cell for model soil-conduit system.

Some typical load-deformation diagrams are shown in Figure 5. This soil load could be either the fill itself or a surcharge load, provided the fill is at least as high as the plane of equal settlement (*5*). The cell has been constructed so that the top and bottom plates are outside of the planes of equal settlement. A very low fill (for example, one less than one pipe diameter above the top of the conduit) must be excluded from the results of this investigation.

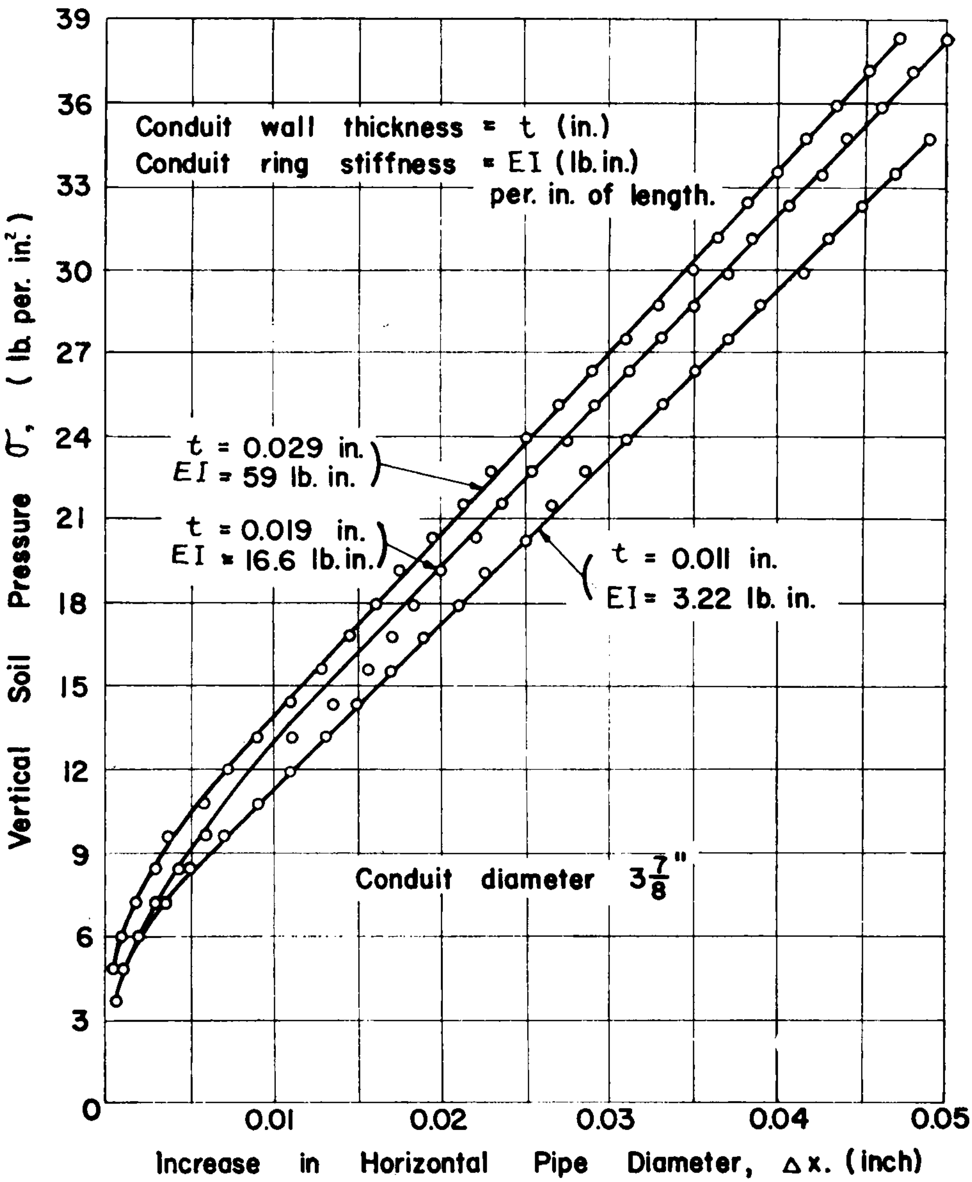

Figure 5. Typical load-deformation curves, showing the minor effect of ring stiffness on conduit deformation.

The second variable considered was the pre-compaction of the soil. This simulates the compaction and tamping carried out in connection with field installations. It was accomplished by loading the cell before the mandrel was removed.

The third variable was the stiffness of the conduit wall, which stiffness has marked influence on the load at which the conduit buckles.

The fourth variable was soil type.

DIMENSION ANALYSES

The primary quantities influencing the performance of a flexible pipe embedded in an earth fill, for a given soil, are:

ρ_0 =	Initial density of soil in contact with the conduit (compaction density before the fill is placed).	FL^{-3}
EI =	The stiffness of the conduit wall per unit length of conduit.	FL
D =	Original mean diameter of the conduit.	L
Δx =	Horizontal increase in diameter of the conduit due to the vertical soil pressure.	L
$(\Delta x)_{max}$ =	Maximum deformation at buckling.	L
σ =	Vertical soil pressure at the level of the top of the the conduit.	FL^{-2}
	$\approx \gamma H$ for high fills wherein	
	γ = total unit weight of the soil fill and	
	H = the height of the fill above the top of the conduit.	
E' =	Modulus of soil reaction	L
w =	Water content of the soil	None

According to the principles of similitude (*3*) it is necessary that all of the primary quantities be independent. This is not true in the case of the modulus of soil reaction E'. For any given soil type the modulus will surely depend on the initial soil density ρ_0 and on the water content w. But both of these are listed as primary quantities, so E' cannot be considered as one of the primary quantities. Moreover, it is reasonable that E' may be different for every different soil type; therefore, until more is known about E' it will be eliminated from consideration by investigating only one soil type at a time. This leaves seven primary quantities, in which two dimensions, force F and length L, are involved. According to the Buckingham π theorem the minimum number of dimensionless parameters, or π-terms, in any mathematical relationship involving a set of primary quantities must be equal to the number of primary quantities minus the number of dimensions—in this case seven (primary quantities) minus two (dimensions) leaves five π-terms. The five π-terms may be written in the general functional relationships:

$$\pi_1 = f(\pi_2, \pi_3, \pi_4, \pi_5) \qquad (2)$$

According to principles of similitude these π-terms must be independent, dimensionless, made up of the seven available primary quantities, and there must be five π-terms in the relationship. Such a relationship may be written as follows:

$$\frac{\Delta x}{D} = f\left(\frac{\sigma}{\rho_0 D}, \frac{EI}{\rho_0 D^4}, w, \frac{(\Delta x)_{max}}{D}\right) \qquad (3)$$

Accordingly, it is possible to vary each of the π-terms on the right-hand side of Eq. 3 holding the other three terms constant, and calculate the left-hand side. It is easily verified that each of these π-terms is dimensionless and independent. Experience with these variables showed that a convenient method of relating them was to plot the left-hand side as an abscissa and the first term on the right as an ordinate. This plot accounts for the influence of the vertical soil pressure on the ring

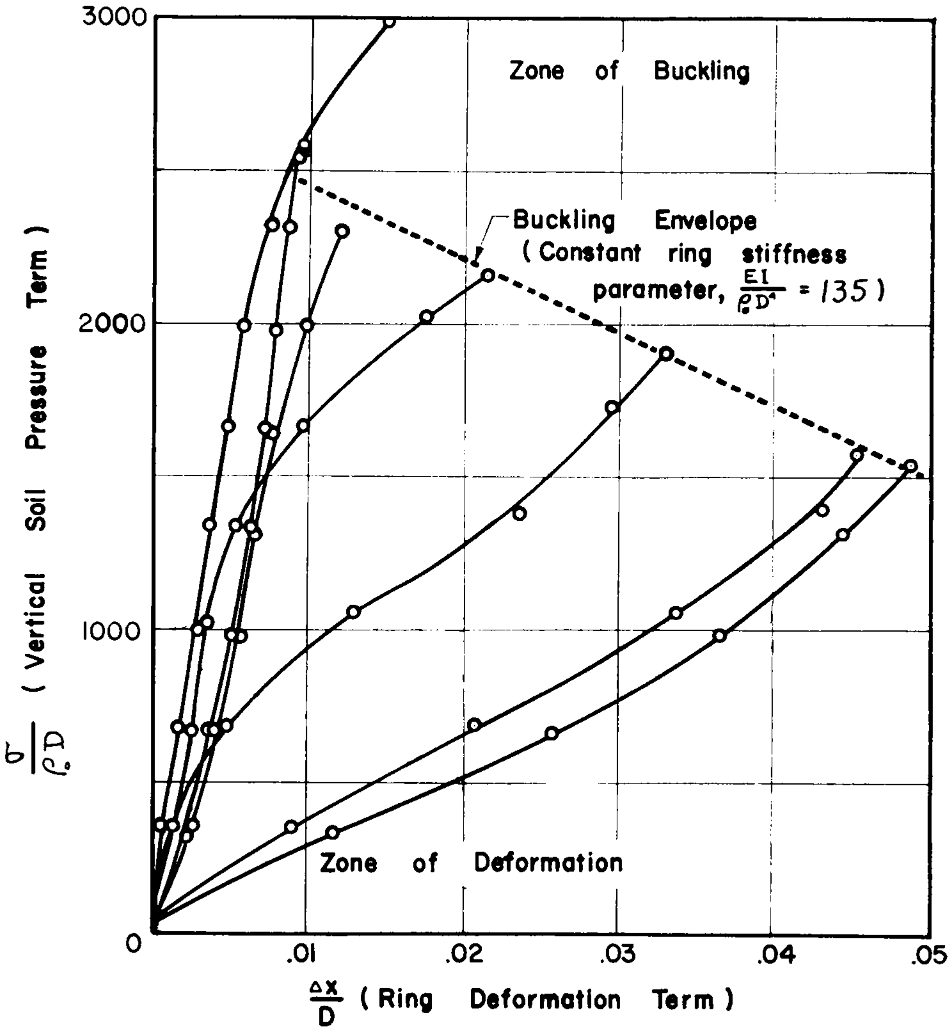

Figure 6. Pressure-deformation curves in sand, showing the buckling envelope for a fairly flexible conduit.

deformation for any given soil-conduit system.

The question arises as to the influence of the conduit ring stiffness on the ring deformation. It has been shown (*9*) that the influence of ring stiffness on the deflection of flexible conduit is comparatively small; that is, the influence is generally less than the accuracy of the study could justify (Fig. 5).

The most interesting result in Figures 6 and 7 is the influence of the ring stiffness on the maximum ring deformation at buckling. In each case there is a buckling envelope below which the conduit will not buckle but above which it will buckle. The ring stiffness parameter, which locates this envelope, depends on the stiffness of the conduit wall. From this series of tests it is difficult to determine exactly the shape of the buckling envelope. Nevertheless, for practical design purposes and within the range of compaction for which the soil fill might normally be placed, it

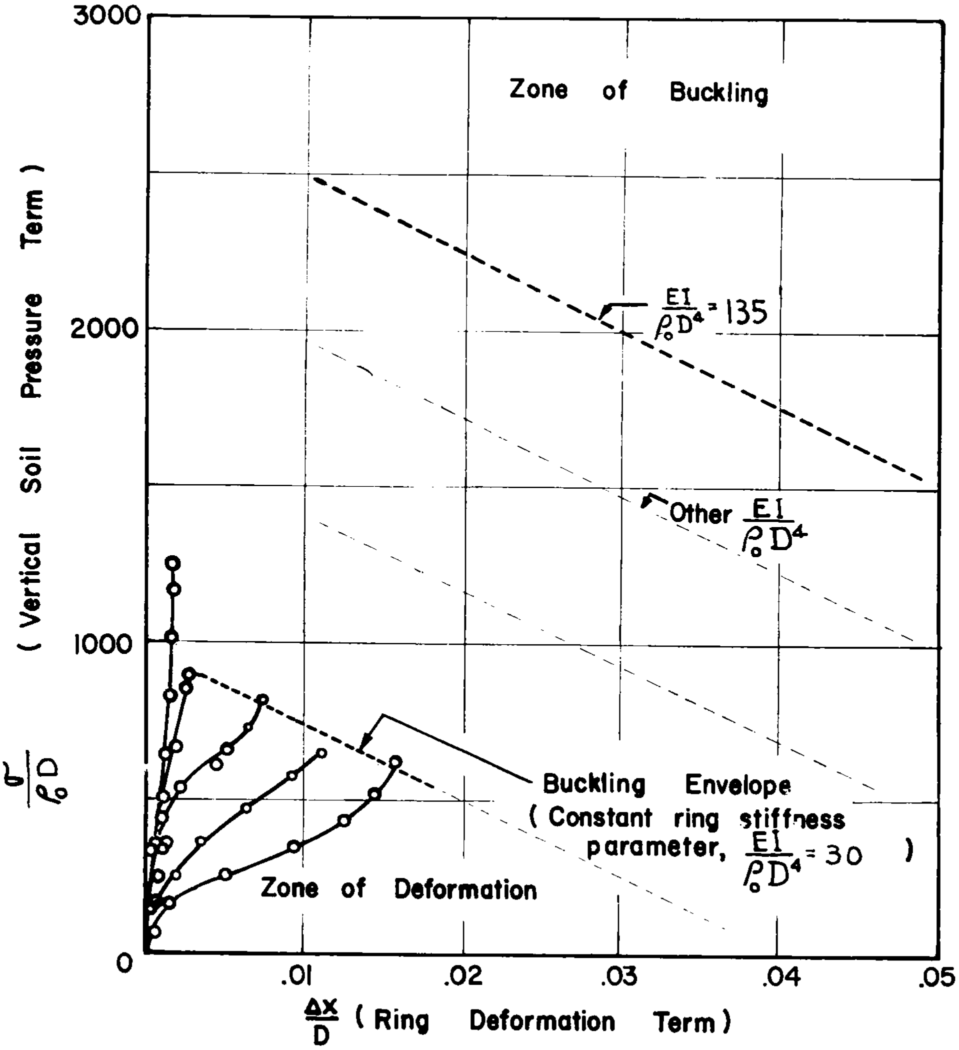

Figure 7. Pressure-deformation curves in sand, showing the buckling envelope for a very flexible conduit.

appears that a straightline ring stiffness envelope (Figs. 6 and 7) might be entirely satisfactory. It would not take an unreasonable amount of testing to develop these buckling envelopes for various soil types. Figure 6 also shows that all pressure-deformation curves start at the origin and follow up the same common pressure-deformation trunk to a point which represents the vertical soil pressure required for initial soil density. In this case sand was used exclusively.

Figures 6 and 7 also show the relationship between ring deformation and vertical soil pressure. This information, too, is important. The load deformation diagrams are not straight lines. Nevertheless, for most practical culvert design purposes a straight line can be assumed with the modification that all lines inter-

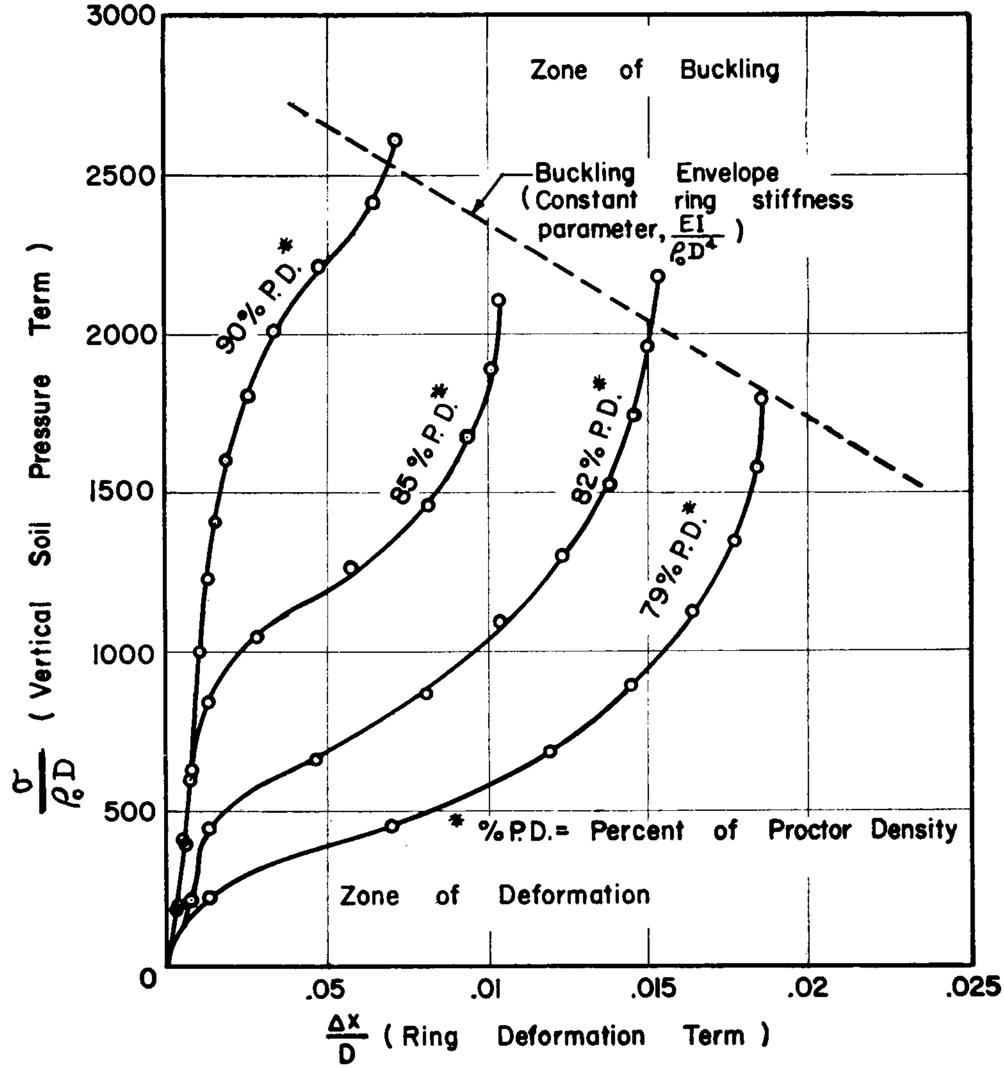

Figure 8. Pressure-deformation curves in clay, showing the buckling envelope for a constant ring stiffness parameter.

sect a common trunk line. Figure 7 also shows the buckling envelope for the more flexible ring (for higher value of ring stiffness parameter) of Figure 6. Also shown are two tentative buckling envelopes for intermediate values of the ring stiffness parameter. This provides a graphical solution of the formula (6) for predicting deformation for a particular soil.

This investigation is by no means a complete solution of the conduit design problem. It is hoped that enough additional investigations of this type may be carried out to provide a more complete solution. For example, the effect of moisture content should be studied.

For practical design purposes each possible failure condition in a soil-conduit system can be investigated independently, providing graphs of dimensionless parameters delineating ring deformation failure conditions and ring buckling failure conditions can be prepared. Also, with some additional research graphs of dimensionless parameters relating conduit deformation to vertical load can be developed for various soil types; for example, clay (Fig. 8).

All tests in this investigation were carried out on model soil conduit systems. As long as the height of soil fill is above the plane of equal settlement, and for the particular sand tested, Figures 6 and 7 apply for any size of conduit (*10*).

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